Backup Power Supply System Analysis

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Abstract. *All electrical or electromechanical systems need electric voltage to function. This voltage is obtained from a distribution network or autonomous power supply. Reliable operation of systems/devices is then largely dependent on the reliability of delivering power supply voltage. The aim of this article is to point out to some aspects of increased reliability possibilities of those systems.*

Keywords

Backup power supply systems, increasing reliability, system reliability.

1. Introduction

With designing and operation of miscellaneous devices and systems, one can meet the requirement for lifetime or period of service that expresses an operational reliability. Most of the devices are composed of subsystems defined by their reliability characteristics. Every electronic or electromechanical device requires electric power. This power is supplied by an internal power supply that is a part of given device or by an external power source, for example distribution network or an autonomous power generator, respectively. Operation of the device will be dependent mostly on the reliability of power supply, because if this fails, then the overall system fails, too. To increase the reliability of important systems (satellite communication systems, medical instruments, weapon systems, etc.), it is vital to back up the power system.

2. Reliability Characteristics

Attendant phenomenons arising during the operation of devices are their failures. Occurrence of failures are usually under influence of a random process. This process of rising failures is usually caused by inner or external reasons that are not possible to predict. Reliability analysis and computations are based on operation data collection and sorting or the result of various functional tests. Generally, the system reliability is defined as a system attribute that is based on the capability to fulfill declared functions in desired time, in given environment and with specified operational conditions. The most important numerical characteristics describing the system reliability are:

- failure probability $Q(t)$,
- no-failure operation probability $R(t)$,
- failure rate $\lambda(t)$,
- failure-probability density $f(t)$,
- mean time between failures (MTBF) $M(t)$.

The failure probability $Q(t)$ in certain time interval $t \in (0; t_n)$ for continuous random variable is given by

$$Q(t) = Q(0; t_n) = \int_0^{t_n} f(t)\, dt, \tag{1}$$

where f(t) is a failure-probability density.

The no-failure operation probability $R(t)$ is a complementary probability describing that in given time interval the system will be functional. It is given by

$$R(t) = 1 - Q(t) = \int_{t_n}^{\infty} f(t)\, dt. \tag{2}$$

The failure rate is one of the most important system property. For continuous random variable it is given by

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - Q(t)}. \tag{3}$$

It expresses the failure probability in an elementary time period with the assumption that until the operation time t the system failure was not detected. The mean time between failures (MTBF) M is the predicted elapsed time between inherent failures of a system. MTBF can be calculated as the arithmetic mean time between failures of a system. The MTBF can be defined in terms of the expected value of the failure-probability function $f(t)$ [9].

$$M = \int_0^\infty t f(t)\, dt = \int_0^\infty R(t)\, dt. \tag{4}$$

2.1. Basic Reliability Models

Basic reliability models interpret the parts of a system by block diagram. Properties of individual parts are presented by statistical indexes of their real reliability values.

1) Serial reliability model

Figure 1 contains n elements (subsystems) arranged in serial.

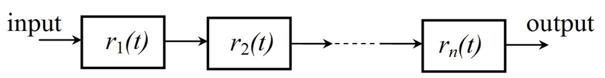

Fig. 1: Serial reliability model.

It represents an example in which an inherent failure of the arbitrary element leads to failure of the overall system. The no-failure operation probability of that system is

$$R(t) = r_1(t)\, r_2(t) \ldots r_n(t) = \prod_{i=1}^{n} r_i(t), \tag{5}$$

where $r_1(t)$ is no-failure operation probability of the first element, $r_2(t)$ is no-failure operation probability of the second element and $r_n(t)$ is no-failure operation probability of the n^{th} element.

Parallel reliability model (Fig. 2) contains m elements arranged in parallel. If one of the elements brakes down then second (backup) element starts to operate.

The failure probability of this model is

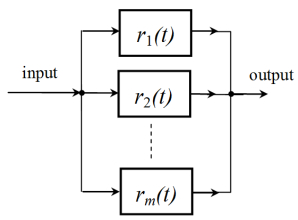

Fig. 2: Parallel reliability model.

$$Q(t) = q_1(t)\, q_2(t) \ldots q_m(t) = \prod_{j=1}^{m} q_j(t), \tag{6}$$

where $q_1(t)$ is a failure probability of the first element, $q_2(t)$ is a failure probability of the second element and $q_n(t)$ is a failure probability of the n^{th} element.

2) Series-parallel reliability model

Figure 3 is an example of real systems composed of n serial connected elements and m elements connected in parallel.

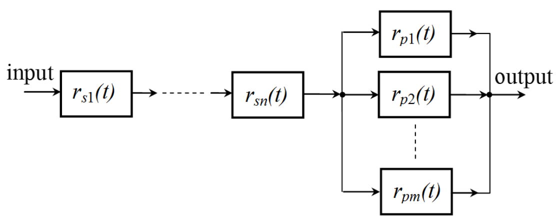

Fig. 3: Series-parallel reliability model.

No-failure operation probability of that scheme is given by

$$\begin{aligned} R(t) &= 1 - Q(t) = 1 - \textstyle\prod_{j=1}^{m} q_j(t) = \\ &= 1 - \textstyle\prod_{j=1}^{m} [1 - r_j(t)]. \end{aligned} \tag{7}$$

3. Methods for Increasing of System Reliability

The increase of system reliability is realized by:

- the selection of suitable elements or subsystems,
- the selection of proper operating mode and operating conditions,
- the realization of periodic service operations,
- the subsystem backup,
- etc.

$$R(t) = 1 - Q_{bck}(t) = 1 - \prod_{i=1}^{m+1} Q_i(t) = 1 - \prod_{i=1}^{m+1} [1 - R_1(t)], \tag{8}$$

$$R(t) = 1 - Q_1^{m+1}(t) = 1 - [1 - R_1(t)]^{m+1}, \tag{9}$$

$$Q_m(t) = \frac{(\lambda_1 t)^m}{m!}, \tag{10}$$

$$R(t) = R_{ON}(t) R_{GN}(t) R_S(t) = \prod_{i=1}^{n} r_{si} \left\{ 1 - \prod_{j=1}^{2} [1 - r_{ONj}(t)] \right\} \left\{ 1 - \prod_{k=1}^{3} [1 - r_{GNk}(t)] \right\}, \tag{11}$$

$$R_{SUB}(t) = R_{ON}(t) R_{GN}(t) R_S(t) = \prod_{i=1}^{n} r_{si} \left[1 - \frac{(\lambda_1 t)^k}{k!} e^{-\lambda_1 t} \right] \left[1 - \frac{(\lambda_1 t)^m}{m!} e^{-\lambda_1 t} \right]. \tag{12}$$

The system backup can be continuous, which means that the backed-up element is connected to secondary element all over its operation. The second possibility of backup is to connect the secondary element only if the backed-up element has a failure. This case is called substitution backup (substitution redundancy). If the backed-up and secondary elements have the same no-failure operation probability $R(t)$ then

If in substitution backup the failure probability is under the influence of Poisson law, then for the occurrence of m failures in given time interval the failure probability is

Power supply system of vital communication, control, defense or medical systems is one of the examples in which the system failure should be minimized. These systems are usually created by two power supply systems with

- On-board supply system – it provides the DC voltage. It is realized in system standby (or turn-off) by electrochemical secondary cells (accumulators),
- AC power supply system – it provides AC voltage from an electric generator.

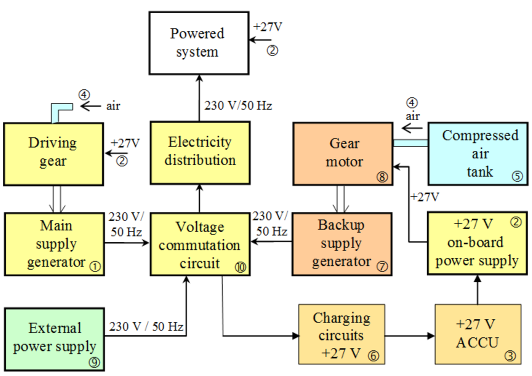

Fig. 4: Example of substitute power supply backup.

As we can see on the Fig. 4, an activation of main AC generator (1) is realized by on-board power supply network (2). A failure of the on-board power supply leads to a malfunction of the main generator too, because it will not be started up.

If there is a requirement to increase system reliability, power supply backup of the on-board power supply and the main AC generator, respectively, must be realized. If an accumulators (3) fail (discharge, capacity loss, ageing process, damage, etc.) then the main AC generator (1) will not to be activated. The accumulators backup can be realized by compressed air (4) in air tank (5) that can activate the main generator (1), too. If the main generator starts, it creates the AC supply voltage that is necessary for activating overall on-board devices and that can charge accumulators (3) over charging circuits (6). The main generator is backed-up twice, by an internal backup generator (7) actuated by a driving gear (8) and an external power supply (9) (mobile AC generator, industrial supply network, etc.). With the main generator (1) failure, the switching on backed-up power supply is realized manually (or automatically) over voltage commutation circuits (10). The external power supply (9) connection is realized only manually.

The no-failure operation probability *R(t)* of backed-up power supply with continuous backup (for example partially loaded) is then possible to evaluate by modifying Eq. (9).

In Eq. (11), $R(t)$ is no-failure operation probability of overall system, $R_{ON}(t)$ is no-failure operation probability of on-board power supply network, $R_{GN}(t)$ is no-failure operation of AC power supply network, $R_S(t)$ is overall no-failure operation probability of system 1 up to n, $r_{si}(t)$ is no-failure operation probability of i^{th} system, $r_{ONj}(t)$ is no-failure operation probability of j^{th} on-board power supply system and $r_{GNk}(t)$ is a no-failure probability of k^{th} power supply generator.

The no-failure operation probability of the backed-up power supply with the substitute redundancy (substitute backup) when power supply backup is inactive can be evaluated by using Eq. (8) and Eq. (10).

In Eq. (12), $R_{sub}(t)$ is no-failure operation probability of the overall system with substitute power supply backup, k is multiple of on-board supply backup; m is multiple of AC power supply backup. As one can see the overall reliability of system is given by a product of probabilities $R_{ON}(t)$, $R_{GN}(t)$ and $R_S(t)$. Increasing of the system reliability is realized by backup of main power supply because if it fails the overall system fails, too.

4. Conclusion

The aim of this article is to show the meaning of the power supply reliability and ability to increase it. Although the described model is focused on military application, it is suitable also for non-military applications where the power supply failure can lead to a malfunction of overall system. As an example one can show communication systems, medical systems, various special industrial systems, etc.

However in specific cases the criteria for time recovery of primary (or backup) power supplies are much more rigid. Some criteria on electrical distribution in medical rooms are defined in Slovak Technical Standard STN 33 2000-7-710:2013-08 (or CSN 33 2000-7-710 in Czech Republic) where the time recovery is in general 120 s and in special emergency power supply backup it is only 15 s (or 0.5 s) [6].

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